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Trustful double auction design for Peer-to-Peer energy trading between interconnected micro-grids with supply–demand imbalance

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ABSTRACT

Peer-to-Peer (P2P) energy trading between Interconnected Micro-Grids (IMGs) presents a promising approach for enhancing the economic advantages for prosumers while mitigating supply–demand imbalances within individual Micro-Grids (MGs). This paper proposes a trustful double auction mechanism for P2P energy trading among prosumers in IMGs, structured into two distinct stages. Initially, concurrent auctions are conducted within each MG to facilitate intra-grid trading, followed by subsequent auctions facilitating inter-grid trading across IMGs. We figure out the allocation and pricing rules that satisfy the required properties in mechanism design even when the auction consists of two stages. Given that energy transactions across IMGs entail non-negligible power losses, equitable allocation of these losses among prosumers is paramount. To address this, we integrate a fair cost distribution methodology into our auction mechanism, implemented by an iterative algorithm. Rigorous analysis substantiates our proposed auction mechanism's incentive compatibility, individual rationality, and budget balance, thereby fostering truthful and voluntary prosumer participation while averting potential market deficits. Numerical analysis underscores the efficacy of our approach, showcasing a significant improvement in P2P transactions and supply–demand balance enhancement compared to trading solely within individual MGs.

1. Introduction

1.1. Motivation and background

The proliferation of Distributed Renewable Resources (DERs) has transformed consumers into active players known as prosumers, embodying a new concept in the energy landscape. Prosumers, whose energy generation exceeds their consumption, actively engage in the energy market by trading surplus energy with other prosumers facing energy shortages. In this context, P2P energy trading emerges as a means of directly transacting power from DERs between local prosumers. Given that MGs offer a conducive environment for energy transactions among neighbors and efficient demand and supply management, P2P energy trading within MGs has garnered significant attention. It is anticipated to bolster prosumers' economic benefits while fostering power system stability through decentralization [1,2]. However, the effectiveness of P2P power transactions can be hampered by disparities in supply and demand resulting from regional uncertainties in power generation and climatic characteristics [3,4]. Particularly, P2P energy trading may become increasingly competitive as tradable energy diminishes due to supply–demand imbalances within MGs. Consequently, prosumers' incentives to participate in P2P energy trading could be significantly diminished, as they may only anticipate marginal economic benefits from such transactions.

Interest in energy exchange within IMGs has surged recently, driven by the need to address challenges stemming from P2P energy trading within individual MGs [5,6]. IMGs represent power systems where multiple MGs are interconnected, facilitating the transmission and exchange of both power and information. The shared power and information infrastructure in IMGs enables coordinated operations among multiple MGs, thereby reducing system uncertainty and enhancing operational flexibility [6]. Expanding P2P energy trading from individual MGs to IMGs presents opportunities to amplify trading opportunities and economic benefits for prosumers. In this context, MGs encountering operational challenges can leverage support from other interconnected MGs within the IMG network. This potential for mutual assistance underscores the significance of exploring a suitable energy trading mechanism within IMGs.

In scenarios where a single MG experiences a significant disparity between power supply and demand, IMGs offer a potential solution by implementing a P2P energy trading market encompassing all prosumers

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within the IMG network. However, this centralized strategy may encounter computational efficiency and privacy challenges, particularly as the number of prosumers and the volume of information shared among MGs increase. Consequently, there is a pressing need to explore decentralized market mechanisms for P2P energy trading in IMGs that can enhance transaction efficiency while minimizing information exchange with other MGs. One alternative solution involves introducing an additional market within IMGs to facilitate P2P transactions among prosumers across MGs, particularly in scenarios where supply–demand imbalances persist after establishment of individual P2P trading markets within each MG. Specifically, this entails considering a two-stage P2P energy trading market, where decentralized P2P markets within each MG precede P2P transactions within the IMGs. This strategy alleviates imbalances within MGs by enabling sellers in MGs with surplus electricity to engage in transactions with buyers in other MGs facing excess demand.

1.2. Literature review

There is a growing interest in the literature regarding the design of market clearing mechanisms for P2P energy trading. This body of literature can be classified into three main approaches: constrained optimization, game theory, and double auction theory. In terms of P2P energy trading models using constrained optimization, [7,8] have put forth Mixed Integer Linear Programming (MILP) based frameworks. A cooperative energy market model for an active Distribution Network was discussed in [7]. [8] devised a MILP-based model that integrates demand response across different household models. Also, [9] introduced a MILP model for transaction networked multi-carrier energy systems, addressing fair operation cost allocation. However, as the network of trading prosumers expands, centralized optimization methods face challenges in computational efficiency and applicability. Responding to this, [10] proposed a decentralized P2P energy market framework employing a multi-agent system, while [11] put forth a distributed operation optimization model. Furthermore, a fully decentralized P2P energy market that can allocate energy losses and transaction fees while considering fairness criteria was designed in [12]. Although optimization models used in market mechanisms can provide optimized solutions in terms of P2P energy transactions and costs, they fail to consider the interactions among participating prosumers that influence their decision-making process.

In [13], a non-cooperative game model was devised to scrutinize the interactions and decision-making processes of sellers equipped with storage units within a smart grid context. Building upon this foundation, [14,15] expanded the scope by incorporating interactions between sellers and buyers, with [16] further extending it to encompass interactions not only between sellers and buyers but also among sellers. Furthermore, game-theoretic frameworks have found application across diverse scenarios within the P2P trading market landscape. Some investigations have centered on trading dynamics among prosumers [17–19], while others have focused on transactions between MGs [20–22], or even exchanges between multi-region interconnected flexible distribution networks [23]. Coalitional games have emerged as a tool for cooperatively modeling P2P trading. In this vein, [19] introduced a cooperative Stackelberg game model for energy transactions involving a retailer and multiple cooperative prosumers. Moreover, [24] devised an energy transaction algorithm grounded in coalitional game theory, fostering greater stability and optimality in MG trading, thereby enhancing both collective and individual benefits. However, it is crucial to recognize the presence of information asymmetry between the market operator and prosumers, stemming from prosumers' possession of private information about the valuations of the power they trade. Consequently, prosumers may strategically misrepresent their valuations to their advantage. Achieving efficient outcomes in the P2P energy trading market is challenging amidst such information asymmetry. Therefore, the market clearing mechanism for P2P trading must be crafted to incentivize prosumers to disclose their private information truthfully, facilitating socially optimal outcomes. Moreover, this mechanism should foster voluntary prosumer participation in the P2P market. While game theory models excel in handling agents' interactions within competitive environments, they do not guarantee truthful disclosure or voluntary participation by agents.

In this context, double auction models have emerged as a prominent solution to addressing these challenges. Double auctions are particularly suited to bilateral trading scenarios, as they encourage sellers and buyers, each possessing private information, to engage truthfully. Specifically, if truthful revelation represents the dominant strategy equilibrium for all agents involved, the auction mechanism is deemed dominant-strategy incentive-compatible. Moreover, an auction mechanism is considered individual-rational if it ensures that agents derive no less utility from participation than from non-participation. Additionally, the mechanism is deemed (weakly) budget-balanced if the total payments made by buyers exceed or equal the total revenue earned by the sellers. Moving forward, various implementations of double auction mechanisms have been explored in the literature about P2P energy trading. For instance, a uniform price double auction is employed in studies such as [25,26], while [27] conducted a comparative economic analysis of single-unit and multi-unit P2P energy trading auction models. Another common approach involves iterative double auction mechanisms, as seen in [28,29], and continuous double auction mechanisms, as explored in [30,31].

Despite the effectiveness of double auctions as a market mechanism for P2P markets, their application within a single MG may fall short of adequately addressing the demand-supply dynamics, especially in instances where the MG exhibits highly imbalanced supply and demand due to regional or climatic characteristics. Consequently, P2P trading within IMGs is anticipated to mitigate such imbalances effectively. As a result, recent attention has been directed towards the design of double auction mechanisms tailored for P2P energy trading within IMGs. Studies such as [32–34] have introduced double auction designs enabling multiple MGs to trade power amongst themselves within IMGs. Additionally, [35] devised a combinatorial auction model for Virtual Power Plants (VPPs) comprising IMGs in demand-side ancillary services markets, comparing the outcomes with Stackelberg game frameworks. To foster active partner selection and increase transaction volume, [36] proposed a distributed incentive mechanism for multiple micro-grid systems, allowing for the submission of multiple bids. In these investigations, MG operators engage in P2P trading auctions on behalf of prosumers to address unmet demand or supply within the MGs. Consequently, prosumers assume the role of price-takers, making it challenging to attribute market power to them. However, a market design enabling prosumers to wield market power and participate in auctions is deemed necessary for the economic benefit of prosumers and the activation of P2P energy trading. In contrast, [37] proposed a hierarchical electricity trading scheme employing a discriminatory k-Double Auction, allowing prosumers to trade energy across various markets. Unlike previous approaches, prosumers in this scheme possess market power and can bid at their desired prices for their demand or supply. However, the auction introduced in [37] failed to meet the requisite properties in mechanism design.

It is worth noting that energy trading between different MGs within IMGs inevitably results in additional power losses [12]. These losses incur costs that must be fairly allocated among prosumers. For instance, [38] investigated methods for distributing these power losses' costs, while [12] proposed an allocation method for power losses, taking into account fairness and prosumers' satisfaction levels. Despite some studies that address power losses, few double auction models have considered the allocation of power losses in energy trading while ensuring incentive compatibility, individual rationality, and budget balance. Our study aims to address this gap by integrating a feasible cost distribution of power loss into the double auction mechanism for P2P energy trading within IMGs.

1.3. Contributions

In this paper, we propose a trustworthy double auction mechanism that is incentive-compatible, individually rational, and budget-balanced, enabling prosumers to trade energy within a single MG and across different MGs. Our focus lies particularly on addressing supply–demand imbalances within MGs experiencing significant disparities in power supply and demand. The double auction framework presented in this paper comprises two stages: (1) In the first stage, simultaneous auctions are conducted for each MG in parallel, facilitating energy trading within individual MGs. The pricing rule for each auction is tailored to the specific supply–demand balance within each MG. (2) In the second stage, a subsequent auction is held between buyers from MG with excess demand and sellers from MG with excess supply, who did not secure transactions in the first stage. This subsequent auction is based on the bid information gathered in the initial stage. By dividing the P2P trading process into two stages, we aim to mitigate imbalances within each MG while minimizing the exchange of information across different MGs. Furthermore, we propose a cost distribution method to allocate the expenses incurred by the pricing rule and power losses, designing a budget-balanced and feasible auction mechanism. The primary contributions of this study are as follows:

(1) We introduce a two-stage double auction mechanism that facilitates P2P energy trading within individual MGs and across IMGs. We figure out the allocation rule and pricing rule of the two-stage double auction and demonstrate that the proposed mechanism satisfies incentive compatibility, individual rationality, and budget balance.
(2) Our novel approach ensures that truthfully revealing private information is the dominant strategy equilibrium for prosumers even if we consider additional subsequent auctions following the initial auction within each MG, aimed at mitigating supply–demand imbalances.
(3) We integrate a feasible cost distribution method into the double auction mechanism, addressing costs resulting from the pricing rule and power losses. To maintain fairness, we allocate costs to participants in proportion to their trading volume. An iterative algorithm has been developed to distribute costs effectively among prosumers, ensuring non-negative utilities and averting any budget deficits in the market.

The remainder of this paper is organized as follows. We introduce the model description in Section 2. In Section 3, we present our double auction mechanism and show some important properties of the auction. In Section 4, we describe the results of the numerical studies. Finally, Section 5 concludes the paper.

2. Problem description

For the sake of simplicity, the present study considers IMGs that consist of two MGs with an imbalance in the supply and demand of power: one MG has an excess of power supply, while the other has an excess of power demand. We assume that the demand and supply of agents are public information, and when the total demand of agents participating in the P2P trading market is greater (or smaller) than the total supply, we consider the MG to have excess demand (excess supply). Suppose two MGs are not only connected to the main power grid but also interconnected to transmit power to each other. In each MG, prosumers are holding distributed energy resources and there is a single operator. We assume that prosumers in these IMGs can exchange power and information with each other through an interconnected power network and a communication network. Fig. 1 illustrates the conceptual structure of the IMGs.

Without loss of generality, we assume that the retail price offered by the main grid is higher than the price at which PV energy can be sold to the main grid. Agents actively participate in the P2P energy trading market to achieve more profitable transactions compared to dealing with the main grid. Their objective is to either sell at a higher price or buy at a lower price within the P2P market. Agents, acting as either buyers or sellers, engage in P2P trading through a double auction mechanism. After the auction concludes, any remaining demand and supply from prosumers that were not successfully traded in the auction are allowed to be bought or sold to the main grid at a predetermined price. We list the notations used throughout the paper in Table 1.

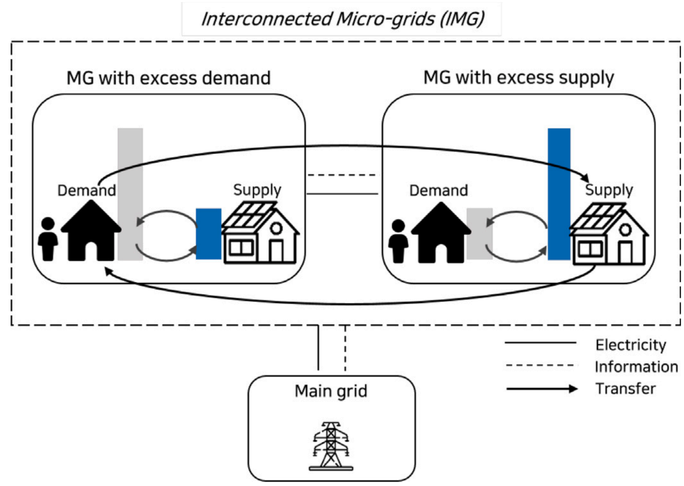

Fig. 1. Structure of the interconnected micro-grids.

In this paper, we attempt to design a multi-unit double auction mechanism for P2P energy trading in IMGs, which enables prosumers to participate as either buyers or sellers in the P2P energy trading market according to the status of power generation and consumption. In the double auction, agents bid for two aspects: the desired price and the desired transaction volume. That is, a buyer i bids for (bid ($\hat{b}_i$), demand (x_i)), whereas a seller j bids for (ask ($\hat{a}_j$), supply (y_j)). Agents have their private information for the valuations of 1 kWh of power, which are b_i and a_j. Therefore, when participating in the auction, they can strategically misreport their values to obtain the results they want, which are $\hat{b}_i$ and $\hat{a}_j$. On the other hand, we assume that demand and supply are common knowledge and continuous value which is greater than 0. Which MG each agent belongs to is also public information. Furthermore, the agents' utilities are assumed to be zero if they do not participate or trade in the P2P trading market. When agents trade between different MGs through the auction, the transactions incur power losses. These losses are proportional to the trading volume and determined according to a coefficient of power loss l.

3. Two stage double auction for interconnected micro-grids

Suppose that all bidders from every MG have submitted bids for both the desired trading price and trading volume. To consider both types of (1) P2P energy trading within a single MG and (2) P2P energy trading between different MGs, we propose a double auction consisting of two stages. The first stage of the auction takes place within each MG, while the second stage occurs between two interconnected MGs. The quasi-linear utility functions of self-interested buyer i and seller j are modeled as (1) and (2), respectively, where trading price p, trading volume q, and cost c are determined through the double auction.

$$U_i(\hat{b}, \hat{a}) = (b_i - p_i(\hat{b}, \hat{a}))q_i(\hat{b}, \hat{a}) - c_i(\hat{b}, \hat{a}) \tag{1}$$

$$U_j(\hat{b}, \hat{a}) = (p_j(\hat{b}, \hat{a}) - a_j)q_j(\hat{b}, \hat{a}) - c_j(\hat{b}, \hat{a}) \tag{2}$$

The flowchart of the proposed double auction mechanism is shown in Fig. 2. The double auction mechanism determines the auction winners, the transaction prices, and the trading volume as follows.

Table 1
Notation.

Parameters	
b_i, s_j	The valuations of buyer i and seller j for 1 kWh of power
$\hat{b}_i, \hat{s}_j$	Buyer i's bid and seller j's ask for 1 kWh of power
x_i^D, y_j^D	Buyer i's demand and seller j's supply in the MG with excess demand
x_i^S, y_j^S	Buyer i's demand and seller j's supply in the MG with excess supply
B_D, S_D	The set of buyers and sellers in the MG with excess demand
$\bar{B}_D, \bar{S}_D$	The set of winning buyers and sellers in the MG with excess demand after the first stage
$\tilde{B}_D, \tilde{S}_D$	The set of final winning buyers and sellers in the MG with excess demand after the second stage
B_S, S_S	The set of buyers and sellers in the MG with excess supply
$\bar{B}_S, \bar{S}_S$	The set of winning buyers and sellers in the MG with excess supply after the first stage
$\tilde{B}_S, \tilde{S}_S$	The set of final winning buyers and sellers in the MG with excess supply after the second stage
TD_D, TS_D	Total demand and supply of winning buyers and sellers in MG with excess demand
TD_S, TS_S	Total demand and supply of winning buyers and sellers in MG with excess supply
Q_{SD}	The total supplied amount transferred from an MG with excess supply to an MG with excess demand
BD_D, BD_S, PL	Budget deficit from the MG with excess demand, from the MG with excess supply, and from the power loss
Decision variables	
$\tilde{p}_D, \tilde{p}_S$	Trading price determined in the first stage in the MG with excess demand and excess supply
$\tilde{p}_I$	Trading price determined in the second stage
q_i^D, q_j^D	Trading volume of buyer i and seller j in the MG with excess demand
q_i^S, q_j^S	Trading volume of buyer i and seller j in the MG with excess supply
c_i^D, c_j^S	Cost for buyer i in the MG with excess demand and seller j in the MG with excess supply

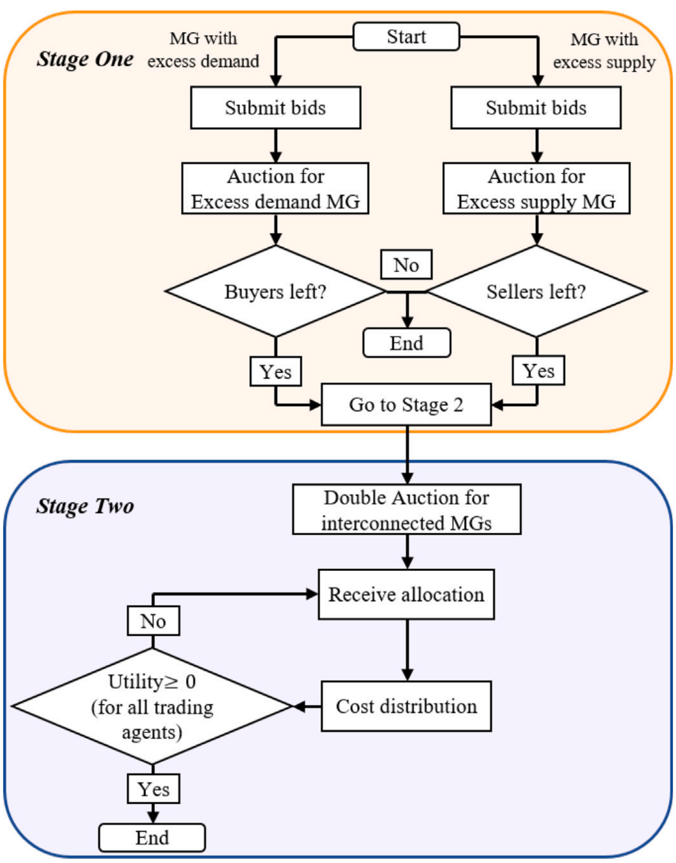

Fig. 2. The flowchart of the double auction mechanism.

3.1. Stage one: double auction within micro-grid

The first stage facilitates transactions between prosumers within the same MG using a modified Multi-unit Double Auction (MDA) mechanism proposed by [39]. It is worth noting that the auction mechanism should vary depending on whether the MG has more power demand or supply. We first state the auction mechanism on the MG with excess demand in detail.

We denote the set of buyers by B_D and the set of sellers by S_D in the MG with excess demand. We let buyers' bids $\hat{b}_i$, $i \in B_D$, be sorted in descending order as (3), while let the sellers' asks $\hat{a}_j$, $j \in S_D$, be sorted in ascending order as (4). If there are agents who have the same bid, their order is randomly assigned.

$$\hat{b}_1 > \hat{b}_2 > \cdots > \hat{b}_m \tag{3}$$

$$\hat{a}_1 < \hat{a}_2 < \cdots < \hat{a}_n \tag{4}$$

We construct the demand and supply function according to the order of bids and asks. Suppose that the demand function and supply function intersect at the demand of buyer K and the supply of seller L. Then there are two possible cases, (A1) and (A2), in which the two functions meet.

(A1) $\hat{b}_{K+1} \le \hat{a}_L \le \hat{b}_K$ and $\sum_{j=1}^{L-1} y_j \le \sum_{i=1}^{K} x_i \le \sum_{j=1}^{L} y_j$

(A2) $\hat{a}_L \le \hat{b}_K \le \hat{a}_{L+1}$ and $\sum_{i=1}^{K-1} x_i \le \sum_{j=1}^{L} y_j \le \sum_{i=1}^{K} x_i$

In both cases, the winning agents are determined as all buyers with indices less than K and all sellers with indices less than L. We define the set of winning buyers as $\bar{B}_D$, and the set of winning sellers as $\bar{S}_D$. The transaction price for sellers in set $\bar{S}_D$ is uniformly determined as $\hat{a}_L$, which is denoted by $\tilde{p}_D$. This pricing rule ensures that there is no relation between winning agents' bids and transaction prices, making the mechanism incentive-compatible. Buyers who did not win the auction in the first stage are allowed to participate in the next second stage. The upper bound of bid prices to participate in the second stage is denoted by t_D and is set equal to $\hat{b}_K$. Other buyers in the same MG may also want to participate in the second stage, so there is an incentive to misreport their bid prices. Therefore, in the MG with excess demand, the transaction price for winning buyers is determined only after the winners of the second stage are established, to prevent misreporting. Additionally, to enhance efficiency, the allocation is determined later based on the overall results of both stages.

In the case of MG with excess supply, the first stage of double auction can be operated similarly except for one key difference: the transaction price of buyers, rather than sellers, is determined at the first stage. Specifically, suppose all buyers whose indices are less than K and all sellers whose indices are less than L win the auction in MG with excess supply by applying the same auction rule. Winning buyers transact at a uniform price of $\tilde{p}_S = \hat{b}_K$, while all winning sellers' transaction price is determined in the second stage. The lower bound of the ask prices to participate in the second stage, which is denoted by t_S, is $\hat{a}_L$.

After the completion of the first stage in each MG, the double auction results are announced to the agents. If there are remaining buyers $i \in (B_D \setminus \bar{B}_D)$ in the MG with excess demand and remaining sellers $j \in (S_S \setminus \bar{S}_S)$ in the MG with excess supply, and $t_D \geq t_S$, the second stage is conducted to facilitate transactions among prosumers across the two connected MGs. Otherwise, the double auction will be terminated completely in the first stage, and the transaction prices for $i \in \bar{B}_D$ and $j \in \bar{S}_S$ will be determined at $\tilde{p}_D$ and $\tilde{p}_S$, respectively. In this case, the allocation of agents in each MG is determined using the same allocation method as the MDA mechanism.

3.2. Stage two: double auction between interconnected micro-grids

The second stage is conducted using the bid information submitted in the first stage, without requiring additional bids or asks. This stage is available only to agents who did not win the first stage of the double auction and submitted bids in the range of $[t_S, t_D]$ during the first stage. There are remaining sellers in the MG with excess demand and remaining buyers in the MG with excess supply who were not awarded in the first stage of the double auction. However, only the remaining buyers in the MG with excess demand and remaining sellers in the MG with excess supply, whose bids and asks fall within the range of $[t_S, t_D]$, participate in the second stage to increase the overall social welfare. It should be noted that power transactions between two different MGs incur power loss that is proportional to a coefficient l and the trading volume.

How the winners and transaction prices are determined in the second stage is similar to that of the first stage. For agents who participate in the second stage of the double auction, we denote the buyers' bids by $\hat{b}^I_i$ for $i \in (B_D \setminus \bar{B}_D)$ and the sellers' asks by $\hat{a}^I_j$ for $j \in (S_S \setminus \bar{S}_S)$. Bids and asks are sorted again and the demand and supply functions are reconstructed according to the sorted order. Suppose that the demand and supply functions intersect at a certain point where the corresponding indices are K and L. Then all buyers with indices less than K and all sellers with indices less than L trade at a uniform price determined as

$$\tilde{p}_I = \frac{\hat{b}^I_K + \hat{a}^I_L}{2} \tag{5}$$

The transaction price for the winning buyers in the MG with excess demand and the winning sellers in the MG with excess supply, which was not determined in the first stage, is uniformly determined as $\tilde{p}_I$ at this stage.

The total supply and demand in each MG by agents who win the double auction throughout the stages can be calculated as follows.

$$TD_D = \sum_{i=1}^{K-1} x^D_i + \sum_{i=1}^{K-1} x^I_i, \quad TS_D = \sum_{j=1}^{L-1} y^D_j \tag{6}$$

$$TD_S = \sum_{i=1}^{K-1} x^S_i, \quad TS_S = \sum_{j=1}^{L-1} y^S_j + \sum_{j=1}^{L-1} y^I_j \tag{7}$$

If there are winning buyers and sellers in the second stage, then $TD_D > TS_D$ and $TD_S < TS_S$ naturally hold. The allocation rule is designed to first resolve the demand and supply generated within each MG to minimize power loss. Therefore, the supply amount $TS_D(TS_S)$ is first traded with the demand $TD_D(TD_S)$. Thus, the trading volume q^D_j is equal to the supply y^D_j for all winning sellers in $\bar{S}_D$. Similarly, $q^S_i = x^S_i$ for all winning buyers in $\bar{B}_S$. To determine the final allocation, we check whether inequality (8) or (9) holds. These inequalities imply an over-demand and an over-supply, respectively.

$$TD_D - TS_D > TS_S - TD_S \tag{8}$$

$$TD_D - TS_D \leq TS_S - TD_S \tag{9}$$

If (8) holds, we follow the Allocation rule 1, and if (9) holds, we follow the Allocation rule 2.

Allocation rule 1.

Step 1. All the winning sellers in two MGs sell their entire volume. However, only the winning buyers in MG with excess supply buy their entire demand.

Step 2. Let the gap g be equal to $(TD_D - TS_D) - (TS_S - TD_S)\cdot(1-l)$. The quantity g represents the unmet demand in the MG with excess demand that every winning seller cannot fulfill. Therefore, it is distributed evenly among all trading buyers in the MG with excess demand, regardless of the order of bid prices. In other words, these buyers will buy electricity up to their demand, excluding the amount of distributed unmet demand.

Step 3. If the distributed unmet demand exceeds the demand of some buyer, we allocate zero trading volume to that buyer. Then the gap g is recalculated and distributed again. This process continues until each buyer is allocated a non-negative volume.

Allocation rule 2.

Step 1. Let the gap g be equal to $(TS_S - TD_S)\cdot(1-l) - (TD_D - TS_D)$. We check whether g is non-negative. If it is, we proceed with Step 2a. Otherwise, we follow Step 2b.

Step 2a. All the winning buyers buy their entire volume. However, only the winning sellers in the MG with excess demand sell their entire supply. In this case, the unmet supply can be calculated as $g' = (TS_S - TD_S) - (TD_D - TS_D)/(1-l)$. All trading sellers in the MG with excess supply will sell electricity up to their supply, excluding the amount of evenly distributed unmet supply.

Step 2b. Negative g implies that there is an unmet demand in the MG with excess demand. Thus, we follow the same process as Step 1 and Step 2 of Allocation rule 1.

Step 3. To prevent agents from receiving a negative allocation, a process that is similar to Step 3 in Allocation rule 1 is also applied in this Step 3.

The sets of final trading agents are determined after the allocation as follows:

$$\tilde{B}_D = \{i | q^D_i > 0, i \in B_D\}, \quad \tilde{S}_D = \{j | q^D_j > 0, j \in \bar{S}_D\}, \tag{10}$$

$$\tilde{B}_S = \{i | q^S_i > 0, i \in \bar{B}_S\}, \quad \tilde{S}_S = \{j | q^S_j > 0, j \in S_S\}, \tag{11}$$

where the trading volume q^D_i, q^D_j, q^S_i, and q^S_j are the results of the Allocation rule.

3.3. Cost distribution

Our pricing mechanism may result in a budget deficit in the market depending on the value of $\tilde{p}_D$, $\tilde{p}_S$, and $\tilde{p}_I$, as shown in Eqs. (12) and (13). Sellers in the set $\tilde{S}_D$ sell their supply at $\tilde{p}_D$, while buyers in the set $\tilde{B}_D$ purchase their demand at a price $\tilde{p}_I$. Similarly, buyers in the set $\tilde{B}_S$ purchase their demand at $\tilde{p}_S$, while sellers in the set $\tilde{S}_S$ sell their supply at a price $\tilde{p}_I$. Consequently, the budget deficit may arise due to the discrepancy between buyers' and sellers' trading prices for the P2P transactions within each MG. In other words, if $\tilde{p}_D > \tilde{p}_I$ or $\tilde{p}_I > \tilde{p}_S$, it will result in a budget deficit and undermine the reliability and stability of the market. In all other situations, a surplus exists, which is assumed to be absorbed by the market. Furthermore, power loss will lead to a budget deficit, as shown in Eq. (14). That is because buyers are charged for the amount they purchase and sellers are paid for the amount they sell. Thus, no payment is made for the amount of

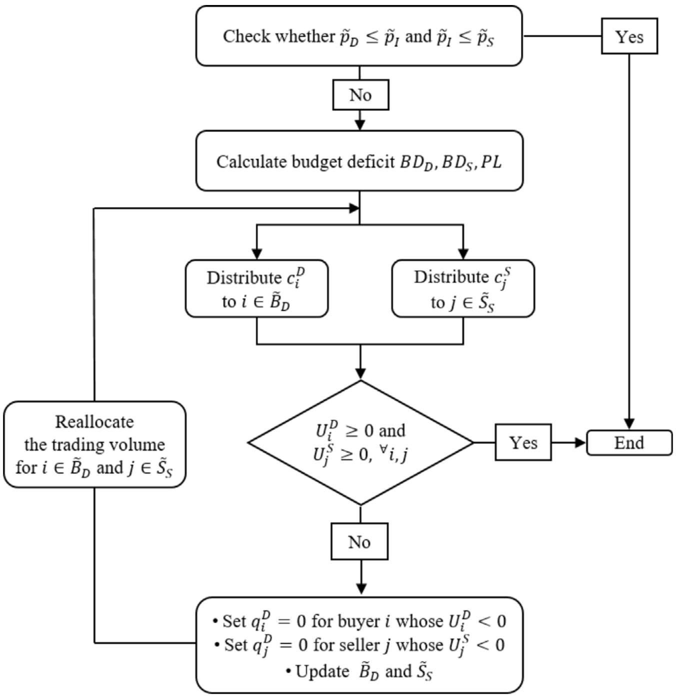

Fig. 3. The flowchart of the cost distribution.

$Q_{SD} \cdot l$, which represents the amount of power loss. The deficits can be calculated as follows and are distributed among the agents as a cost.

$$BD_D = (\tilde{p}_D - \tilde{p}_I) \cdot TS_D \tag{12}$$

$$BD_S = (\tilde{p}_I - \tilde{p}_S) \cdot TD_S \tag{13}$$

$$PL = Q_{SD} \cdot l \cdot \tilde{p}_I \tag{14}$$

The flowchart of the proposed cost distribution method is described in Fig. 3. We allocate the cost to the beneficiaries of the double auction between MGs. That is, we distribute BD_D to the buyers in the set $\tilde{B}_D$ and distribute BD_S to the sellers in the set $\tilde{S}_S$. PL is distributed to both the buyers in $\tilde{B}_D$ and the sellers in $\tilde{S}_S$. The distribution amount is proportional to the agents' trading volume as follows:

$$c_i^D = \frac{BD_D \cdot q_i^D}{\sum_{i \in \tilde{B}_D} q_i^D} + \frac{PL \cdot q_i^D}{\sum_{i \in \tilde{B}_D} q_i^D + \sum_{j \in \tilde{S}_S} q_j^S} \text{ for } i \in \tilde{B}_D \tag{15}$$

$$c_j^S = \frac{BD_S \cdot q_j^S}{\sum_{j \in \tilde{S}_S} q_i^S} + \frac{PL \cdot q_j^S}{\sum_{i \in \tilde{B}_D} q_i^D + \sum_{j \in \tilde{S}_S} q_j^S} \text{ for } j \in \tilde{S}_S \tag{16}$$

The agents' utility, including the distributed cost, must be non-negative to ensure individual rationality. If the total utility of some agents becomes negative due to the cost, we adjust their allocations and costs to zero, resulting in zero utility for those agents. This adjustment affects the sets $\tilde{B}_D$ and $\tilde{S}_S$. Thus, for the buyers in the updated set $\tilde{B}_D$ and the sellers in the updated set $\tilde{S}_S$, we then reallocate the trading volume according to the Allocation rule and redistribute the cost. It should be noted that after the reallocation, the values of BD_D, BD_S, and PL remain unchanged. Only the cost imposed on each agent needs to be recalculated. We repeat this process until the corresponding deficit is completely resolved, and there are no agents with negative utility. In other words, the agents either pay a cost proportional to their trading volume and receive a positive allocation, or they receive a zero allocation. This method of cost distribution discourages agents from strategically misreporting their bids to lower the cost distribution, as the amount of distribution is independent of their bids and asks, which are their private information. Therefore, our mechanism always guarantees full recovery of the budget deficit and agents' truth-telling.

3.4. Properties

In this subsection, we show that the two-stage double auction mechanism for IMGs is incentive-compatible, individually rational, and budget-balanced.

Theorem 1. *The two-stage double auction mechanism is a dominant strategy incentive-compatible under the assumption that the submitted information on demands and supplies is public.*

Proof. The proof of Theorem 1 follows similar arguments as Vickrey's and Huang's arguments [39,40]. Suppose that a buyer i in the MG with excess supply with a valuation b_i submits a bid $\hat{b}_i$. There are two possible cases: $b_i \ge \tilde{p}_S$ or $b_i < \tilde{p}_S$. For each case, we show that there is no incentive for buyer i to deviate from truth-telling.

First, if $b_i \ge \tilde{p}_S$, overbidding will not increase buyer i's utility since the price is determined uniformly for buyers in set B_S and it is independent of the bids of buyers in set $\tilde{B}_S$. If buyer i underbids, either i may lose the auction or i will gain the same utility as if i had bid truthfully. Second, if $b_i < \tilde{p}_S$ and buyer i overbids, buyer i may win the auction but receive the negative utility. Even if buyer i does not win the auction, the utility will be the same as if i had bid b_i. Underbidding would lead to zero utility just like when buyer i bids truthfully. Therefore, it is the best response for this buyer to bid truthfully regardless of the bids of other agents.

Similarly, suppose a seller j in the MG with excess supply with a valuation a_j submits an ask $\hat{a}_j$. We also have two case: $a_j \ge \tilde{p}_I$ or $a_j < \tilde{p}_I$. If $a_j \ge \tilde{p}_I$, overbidding will not change seller j's utility, and the cost paid by seller j is independent of their decision. Underbidding is not incentivized for the same reasons as buyers in the MG with excess supply. If $a_j < \tilde{p}_I$, the proof follows a similar logic as the case for buyers. Furthermore, it can be shown that buyers and sellers in the MG with excess demand also have no incentive to deviate from truth-telling, using arguments similar to those used for agents in the MG with excess supply.

Lastly, let us consider agents who win the auction but only trade part of their demand or supply because of the unmet demand or supply. However, no agent can lower the amount of quantity reduction during allocation by misreporting their bids or asks. Therefore, incentive compatibility is proved under the assumption that the demands and supplies are public information. □

Theorem 2. *The two-stage double auction mechanism is individually rational and (ex-post) budget-balanced.*

Proof. Under the two-stage double auction mechanism for IMGs, buyers in B_D and B_S whose bids are less than or equal to $\tilde{p}_I$ and $\tilde{p}_S$, respectively, do not trade in the P2P trading market. Similarly, sellers in S_D and S_S whose asks are greater than or equal to $\tilde{p}_D$ and $\tilde{p}_I$, respectively, do not trade. Moreover, our mechanism ensures that buyers in $\tilde{B}_D$ and sellers in $\tilde{S}_S$ obtain non-negative utility after the cost distribution. As a result, the two-stage double auction mechanism is individually rational.

Through the process of checking whether there is a budget deficit and distributing the cost incurred from the P2P market, our mechanism always ensures the complete recovery of the budget deficit that occurred during the auction. Therefore, the two-stage double auction mechanism is budget-balanced. □

4. Numerical analysis

In this section, we analyze the performances of our double auction mechanism on social welfare, trading volume, and the number of trading agents. We compare the performances of our mechanism with those of the MDA mechanism. We further examine how the degree of supply–demand imbalance within each MG affects the auction results.

Table 2
Comparison of performances between the proposed mechanism and the MDA mechanism.

			Social welfare (KRW)	Buying volume (kWh)	Selling volume (kWh)	Trading buyers	Trading sellers
MDA mechanism	MG with ED	Mean	90.64	3.38	3.38	7.13	6.88
		Std	22.09	0.60	0.60	1.27	1.18
		Min	25.13	0.92	0.92	2.00	2.00
		Max	154.02	4.71	4.71	10.00	9.00
Proposed mechanism	MG with ED	Mean	**111.91**	**5.75**	**3.44**	**12.70**	**6.88**
		Std	27.09	1.38	0.60	2.94	1.18
		Min	45.04	2.36	0.92	5.00	2.00
		Max	190.21	10.31	4.87	21.00	9.00
MDA mechanism	MG with ES	Mean	88.28	3.30	3.30	6.76	6.97
		Std	20.93	0.52	0.52	1.03	1.14
		Min	33.04	1.57	1.57	3.00	3.00
		Max	147.86	4.61	4.61	9.00	10.00
Proposed mechanism	MG with ES	Mean	**110.37**	**3.37**	**5.73**	**6.76**	**12.49**
		Std	25.16	0.52	1.35	1.03	2.88
		Min	47.52	1.57	2.58	3.00	6.00
		Max	192.88	4.72	10.76	9.00	21.00

4.1. Parameter setting

The following settings were adopted to conduct the analysis. Consider two connected MGs, one with excess demand and the other with excess supply, along with a P2P energy trading market for them. We assume that there are 35 buyers and 10 sellers in the MG with excess demand and 10 buyers and 35 sellers in the MG with excess supply. All agents are residential prosumers who generate electricity using small-scale solar panels of 3 kW each. Although the amount of electricity generated and consumed varies for each agent and at different times of the trading period, we assume the following numerical values to analyze the mechanism's performance and the impact of supply–demand imbalance. We assume that the demand and supply of buyers and sellers all follow a normal distribution $N(0.5, 0.05^2)$. We define supply–demand imbalance as the difference in the proportion of total bid demand and total bid supply in each MG. Therefore, under the assumed situation, we can see an imbalance of about 3.5 times within each MG. We assume that the valuations for the buyers' electricity purchases and the sellers' electricity sales both follow a uniform distribution of $U(100, 150)$. Finally, we assume a power loss rate of 2.5%, which is expected to be lower than the Korean overall power loss rate of 3.5%, for power trading between the MGs.

4.2. Results

We compare the performance of the proposed double auction mechanism with the MDA mechanism for two separate MGs. That is, we utilize the MDA mechanism, which is applied in a scenario where P2P trading is only possible within each MG and trading between different MGs is not allowed. To achieve reliable results, we repeated each auction mechanism 1000 times and the presented results are their average. The analysis was performed on a PC with a 3.6 GHz Intel Core i7-7700 CPU and 8 GB RAM under Windows 10. All computations were conducted using Python.

Table 2 shows the results of the two auction mechanisms for each MG, including excess demand (ED) and excess supply (ES). From Table 2, the proposed mechanism leads to an increase in social welfare and trading volume for both MGs even if the mechanism incurs various costs. In the MDA mechanism, the buying volume and selling volume within each MG are equal, whereas in our double auction mechanism, the buying volume in the MG with excess demand and the selling volume in the MG with excess supply significantly increase. This demonstrates that our mechanism effectively mitigates the supply–demand imbalance within both MGs. The number of trading sellers in MG with excess demand and the number of trading buyers in MG with excess supply yield similar results for both mechanisms. This is because the second stage of our double auction is for P2P transactions between MGs for remaining buyers in MG with excess demand and remaining sellers in MG with excess supply who could not make transactions in the first stage. As Table 2 illustrates, the standard deviation in social welfare is relatively large. This can be attributed to the assumption that the valuations of both buyers and sellers follow a uniform distribution U(100, 150).

Table 3
Welch's t-test results.

		Mean difference	t-statistics	p-value
MG with ED	Social welfare	−21.26	19.24	0.00
	Buying volume	−2.36	49.61	0.00
	Selling volume	−0.06	2.31	0.02
	Trading buyers	−5.57	55.03	0.00
	Trading sellers	0	0	1.00
MG with ES	Social welfare	−22.08	21.34	0.000
	Buying volume	−0.06	2.87	0.004
	Selling volume	−2.42	52.93	0.00
	Trading buyers	0	0	1.00
	Trading sellers	−5.52	56.40	0.00

The Welch's t-test results supporting the average results presented in Table 2 are provided in Table 3. Judging by the p-values, there appear to be significant differences in the outcomes of social welfare, buying volume, and selling volume between the two auction mechanisms in each MG. However, as Table 2 indicates, there is no significant difference in the average number of trading sellers in MG with ED and trading buyers in MG with ES between the two mechanisms.

Fig. 4 depicts the variation in social welfare for each MG under both mechanisms as the power loss rate ranges from 1 to 4 in increments of 0.5. Regardless of the power loss rate, social welfare under the proposed mechanism consistently surpasses that under the MDA mechanism. However, there is a tendency for social welfare under the proposed mechanism to decrease as the loss rate increases.

Similarly, Fig. 5 illustrates the results of the number of trading buyers in MG with ED and the number of trading sellers in MG with ES as the power loss rate changes. The number of trading agents also consistently favors the proposed mechanism and exhibits a diminishing trend as the loss rate increases. Nonetheless, compared to social welfare, the magnitude of change in the number of trading agents is relatively smaller.

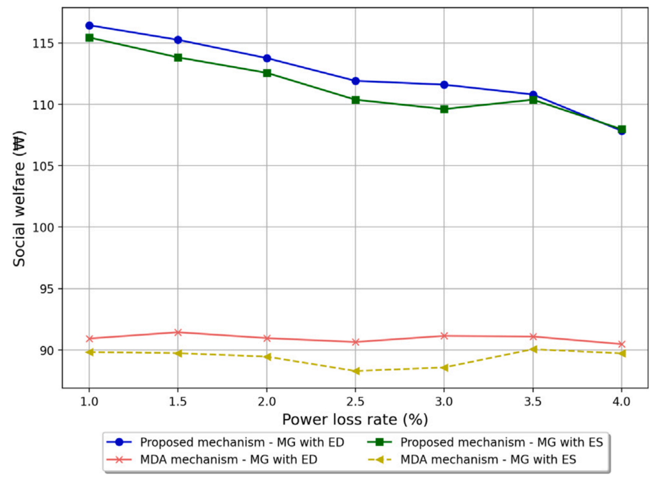

Fig. 4. Impact of power loss rate on social welfare.

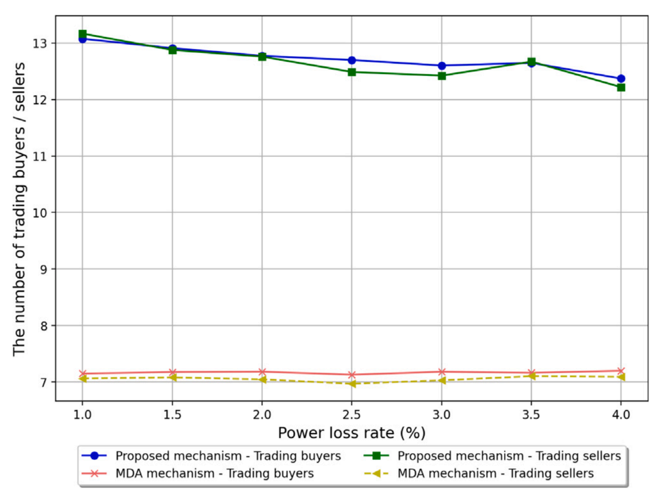

Fig. 5. Impact of power loss rate on the number of trading agents.

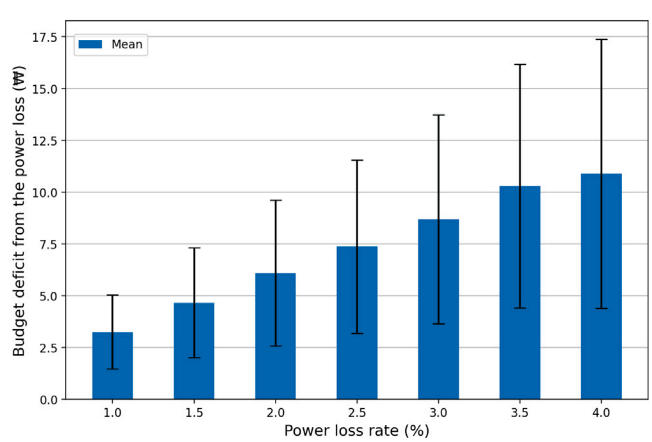

Fig. 6. Impact of power loss rate on the budget deficit from the power loss.

[Fig. 6](#) illustrates the impact of loss rate on deficit caused by power loss and the corresponding standard deviation of the results. As the loss rate increases, the deficit exhibits nearly linear growth, accompanied by a corresponding increase in standard deviation.

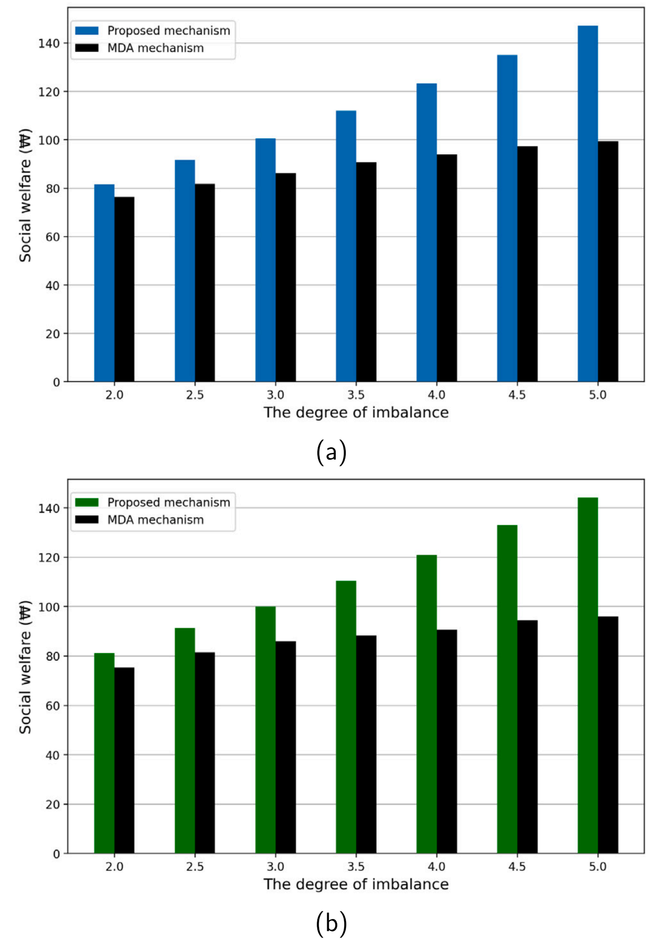

Fig. 7. Impact of imbalance degree on social welfare (a) MG with excess demand (b) MG with excess supply.

Assuming 10 sellers in the MG with excess demand and 10 buyers in the MG with excess supply, we observe the performance changes as we adjust the number of buyers in the MG with excess demand and sellers in the MG with excess supply based on the degree of supply–demand imbalance. Fig. 7 presents the social welfare results as affected by the degree of supply–demand imbalance. In both mechanisms, the social welfare in each MG gradually increases as the imbalance increases. However, the proposed double auction exhibits a greater and sharper increase in social welfare compared to the MDA mechanism, and the gap between them widens as the imbalance increases. More agents are unable to trade within the MG as the imbalance increases, leading to their participation in the second stage of our mechanism.

Figs. 8 and 9 show the trading volumes of buyers and sellers for each MG according to the degree of supply–demand imbalance. In both mechanisms and both MGs, the trading volumes of buyers and sellers increase as the degree of imbalance increases, but our mechanism shows a steeper increase. On the other hand, as shown in Figs. 8(b) and 9(a), the trading volumes of sellers in the MG with excess demand and buyers in the MG with excess supply are not significantly affected by the imbalance. Because the number of these sellers and buyers is fixed at 10 each, and they only participate in the first stage.

Fig. 10 illustrates the impact of the imbalance degree on transaction prices determined by the proposed and the MDA mechanisms. In Fig. 10, p_{ED}^{MDA} and p_{ES}^{MDA} represent the prices determined in MG with ED and MG with ES, respectively, through the MDA mechanism. As the imbalance increases, $\tilde{p}_D$ and p_{ED}^{MDA} increase, while $\tilde{p}_S$ and p_{ES}^{MDA} decrease. This trend arises from heightened buyer competition in the MG with

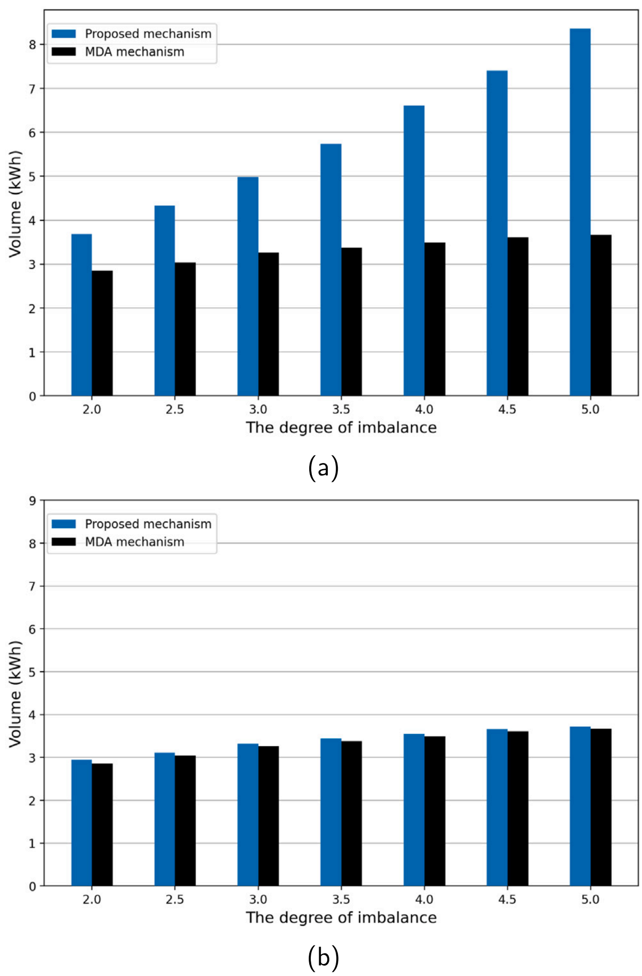

Fig. 8. Impact of imbalance degree on trading volumes in MG with excess demand. (a) Buying volume. (b) Selling volume.

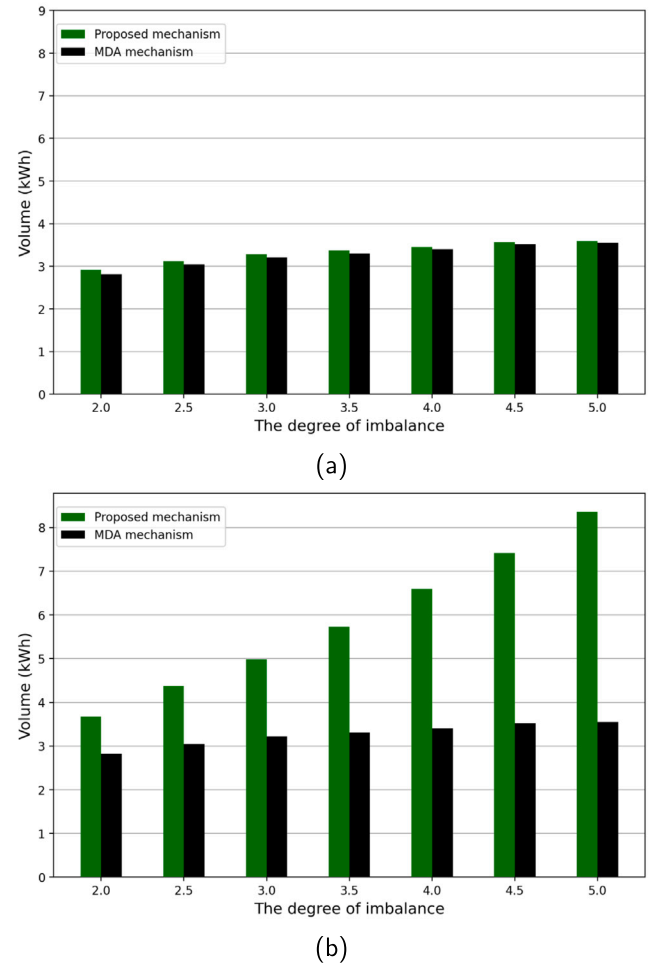

Fig. 9. Impact of imbalance degree on trading volumes in MG with excess supply. (a) Buying volume. (b) Selling volume.

excess demand and intensified seller competition in the MG with excess supply. Conversely, $\tilde{p}_I$ maintains a relatively constant level, positioned between $\tilde{p}_D$ and $\tilde{p}_S$, reflecting the symmetric supply–demand imbalance across the two MGs.

The budget deficit analysis results are shown in Fig. 11. As the imbalance increases, both BD_D, BD_S, and PL increase. In particular, it can be seen that most of the deficit originates from BD_D and BD_S. As the imbalance increases, the differences between $\tilde{p}_D$ and $\tilde{p}_I$, and between $\tilde{p}_S$ and $\tilde{p}_I$ increase as shown in Fig. 10, resulting in an increase in BD_D and BD_S. The amount of PL increases due to increasing transactions between the two MGs as the imbalance grows. However, even after paying a cost, the social welfare of each MG is sufficiently large regardless of the degree of imbalance. Therefore, if we consider a situation where agents pay a fee for P2P energy trading in IMGs, there is a solution to solve the deficit with the fee paid by these agents. Although further discussions are needed to determine the amount of the fee, this realistic approach could significantly improve the efficiency of our mechanism.

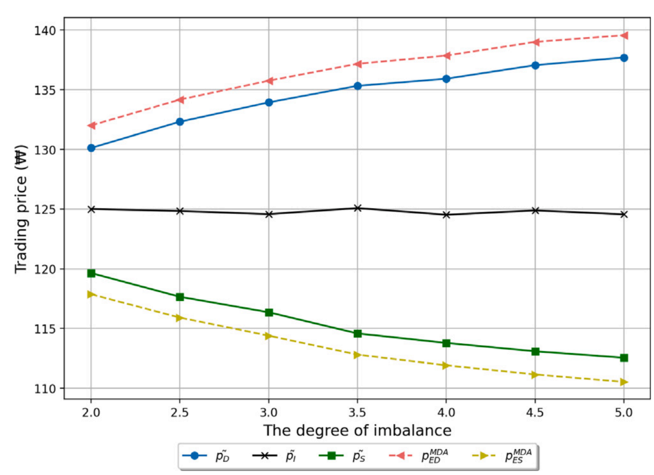

Fig. 10. Impact of imbalance degree on transaction prices.

The preceding analyses operate under the assumption of a similar degree of supply–demand imbalance across the two MGs. Now, we delve into the assessment of social welfare within each MG when two MGs with asymmetric imbalances partake in the double auction. Figs. 12 and 13 present the average social welfare attained through 100 repetitions of our auction mechanism, showcasing scenarios where the supply–demand imbalance values within each MG range from 2 to 5. Remarkably, the MG with excess demand (supply) experiences an enhancement in social welfare upon engaging in P2P transactions with the MG possessing more supply (demand). Therefore, the proposed auction mechanism can be effective for the two MGs with asymmetric imbalances as well.

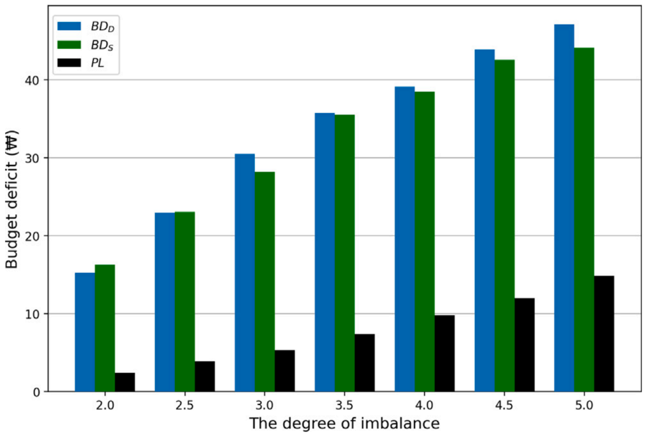

Fig. 11. Impact of imbalance degree on the amount of the budget deficits.

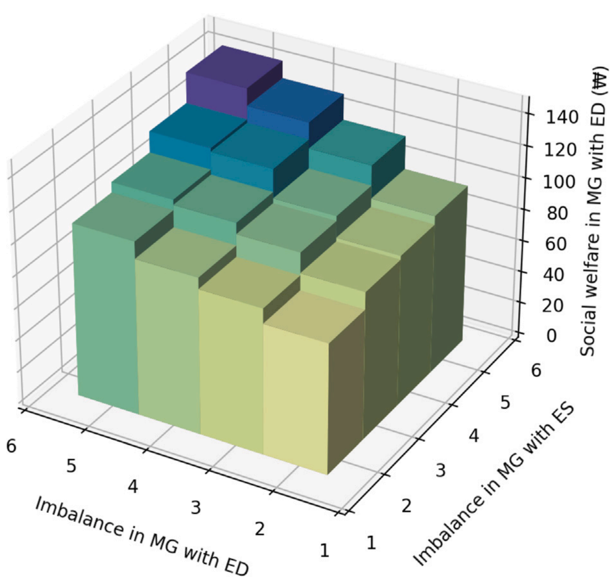

Fig. 12. Social welfare of the MG with excess demand when two MGs have asymmetric imbalance degree.

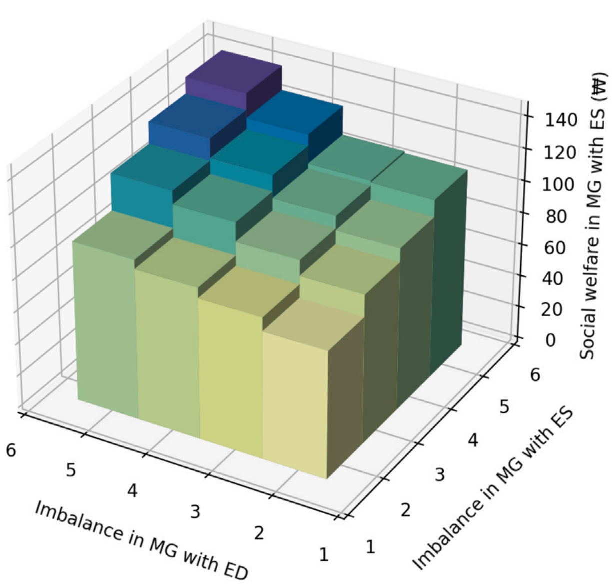

Fig. 13. Social welfare of the MG with excess supply when two MGs have asymmetric imbalance degree.

5. Conclusion

In this study, we designed a two-stage double auction mechanism for P2P energy trading within MGs and across IMGs, aiming to address supply–demand imbalances within individual MGs. The first stage involves simultaneous intra-MG auctions, followed by inter-MG auctions for buyers with excess demand and sellers with excess supply. We have identified the pricing rule consisting of $\tilde{p}_D$, $\tilde{p}_S$, and $\tilde{p}_I$, as well as the allocation rule which varies depending on over-demand and over-supply scenarios. We introduced a fair cost distribution method that addresses deficits and power loss costs and an iterative implementation algorithm. Theorems 1 and 2 demonstrated the proposed mechanism's incentive compatibility, individual rationality, and ex-post budget balance.

Through comparative evaluations under various market scenarios, we gleaned valuable insights. Firstly, our mechanism consistently outperformed the MDA mechanism in terms of social welfare and trading volume for each MG, particularly benefiting buyers with excess demand and sellers with excess supply. Secondly, as the degree of supply–demand imbalance increases, the performance gap between the two mechanisms widened, notably in terms of social welfare, trading volume, and the number of trading agents. Lastly, facilitating P2P transactions between an MG with higher supply (or demand) and an MG with excess demand (or supply) amplified social welfare within the latter MG.

Our double auction mechanism is feasible for real energy trading markets, given the establishment of infrastructure for inter-MG power trading and communication technologies for information sharing. Consequently, our research holds significant managerial implications. It can enhance overall resource efficiency and system stability by addressing supply–demand imbalances and redistributing energy resources. Also, by promoting truthful revelation as the dominant strategy among participants, our mechanism fosters trust, transparency, and efficiency in the market.

There are several ways to improve upon the present work. Firstly, while we assume a uniform power loss rate for inter-MG transactions, considering a variable rate based on prosumers' distance could be more practical. In such cases, future works can extend the mechanism to determine efficient prosumers' matching post-auction, after determining the auction winners and allocations. Secondly, factors like reliability and capacity, beyond price, are vital in determining auction winners. Exploring multi-attribute mechanisms in future studies could address this. Lastly, as the use of Energy Storage Systems increases, treating demands and supplies as private information might be more suitable. Therefore, designing a two-dimensional double auction that considers prices and quantities as private information for P2P energy trading in IMGs could be a challenging direction for future research.

CRediT authorship contribution statement

Jisu Sim: Writing – original draft, Visualization, Software, Methodology, Investigation, Conceptualization. **Deok-Joo Lee:** Writing – review & editing, Supervision, Funding acquisition. **Kiho Yoon:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] Tushar W, Saha TK, Yuen C, Smith D, Poor HV. Peer-to-peer trading in electricity networks: An overview. IEEE Trans Smart Grid 2020;11(4):3185–200.
[2] Tushar W, Yuen C, Saha TK, Morstyn T, Chapman AC, Alam MJE, Hanif S, Poor HV. Peer-to-peer energy systems for connected communities: A review of recent advances and emerging challenges. Appl Energy 2021;282:116131.
[3] Wei C, Shen Z, Xiao D, Wang L, Bai X, Chen H. An optimal scheduling strategy for peer-to-peer trading in interconnected microgrids based on RO and Nash bargaining. Appl Energy 2021;295:117024.
[4] Ahmed HM, Sindi HF, Azzouz MA, Awad AS. An energy trading framework for interconnected AC-DC hybrid smart microgrids. IEEE Trans Smart Grid 2022.
[5] Zou H, Mao S, Wang Y, Zhang F, Chen X, Cheng L. A survey of energy management in interconnected multi-microgrids. IEEE Access 2019;7:72158–69.
[6] Chen B, Wang J, Lu X, Chen C, Zhao S. Networked microgrids for grid resilience, robustness, and efficiency: A review. IEEE Trans Smart Grid 2020;12(1):18–32.
[7] Zhong W, Xie S, Xie K, Yang Q, Xie L. Cooperative P2P energy trading in active distribution networks: An MILP-based Nash bargaining solution. IEEE Trans Smart Grid 2020;12(2):1264–76.
[8] Görgülü H, Topçuoğlu Y, Yaldız A, Gökçek T, Ateş Y, Erdinc O. Peer-to-peer energy trading among smart homes considering responsive demand and interactive visual interface for monitoring. Sustain Energy Grids Netw 2022;29:100584.
[9] Dorahaki S, Sarkhosh A, Rashidinejad M, Salehizadeh MR, MollahassaniPour M. Fairness in optimal operation of transactive smart networked modern multi-carrier energy systems: A two-stage optimization approach. Sustain Energy Technol Assess 2023;56:103035.
[10] Gökçek T, Turan MT, Ateş Y. A new decentralized Multi-agent system for Peer-to-Peer energy market considering variable prosumer penetration with privacy protection. Sustain Energy Grids Netw 2024;101328.
[11] Ruan H, Gao H, Qiu H, Gooi HB, Liu J. Distributed operation optimization of active distribution network with P2P electricity trading in blockchain environment. Appl Energy 2023;331:120405.
[12] Zare A, Mehdinejad M, Abedi M. Designing a decentralized peer-to-peer energy market for an active distribution network considering loss and transaction fee allocation, and fairness. Appl Energy 2024;358:122527.
[13] Wang Y, Saad W, Han Z, Poor HV, Başar T. A game-theoretic approach to energy trading in the smart grid. IEEE Trans Smart Grid 2014;5(3):1439–50.
[14] Liu N, Cheng M, Yu X, Zhong J, Lei J. Energy-sharing provider for PV prosumer clusters: A hybrid approach using stochastic programming and stackelberg game. IEEE Trans Ind Electron 2018;65(8):6740–50.
[15] Anoh K, Maharjan S, Ikpehai A, Zhang Y, Adebisi B. Energy peer-to-peer trading in virtual microgrids in smart grids: A game-theoretic approach. IEEE Trans Smart Grid 2019;11(2):1264–75.
[16] Jiang Y, Zhou K, Lu X, Yang S. Electricity trading pricing among prosumers with game theory-based model in energy blockchain environment. Appl Energy 2020;271:115239.
[17] Zhang C, Wu J, Zhou Y, Cheng M, Long C. Peer-to-Peer energy trading in a Microgrid. Appl Energy 2018;220:1–12.
[18] Paudel A, Chaudhari K, Long C, Gooi HB. Peer-to-peer energy trading in a prosumer-based community microgrid: A game-theoretic model. IEEE Trans Ind Electron 2018;66(8):6087–97.
[19] Li G, Li Q, Liu Y, Liu H, Song W, Ding R. A cooperative Stackelberg game based energy management considering price discrimination and risk assessment. Int J Electr Power Energy Syst 2022;135:107461.
[20] Yan M, Shahidehpour M, Paaso A, Zhang L, Alabdulwahab A, Abusorrah A. Distribution network-constrained optimization of peer-to-peer transactive energy trading among multi-microgrids. IEEE Trans Smart Grid 2020;12(2):1033–47.
[21] Ali L, Muyeen S, Bizhani H, Ghosh A. A peer-to-peer energy trading for a clustered microgrid–Game theoretical approach. Int J Electr Power Energy Syst 2021;133:107307.
[22] Wang L, Zhang Y, Song W, Li Q. Stochastic cooperative bidding strategy for multiple microgrids with peer-to-peer energy trading. IEEE Trans Ind Inf 2021;18(3):1447–57.
[23] Zhao J, Tian Z, Ji H, Ji J, Yan J, Wu J, Li P, Wang C. Peer-to-Peer electricity trading of interconnected flexible distribution networks based on Non-Cooperative games. Int J Electr Power Energy Syst 2023;145:108648.
[24] Sun R, Wang L, Song W, Li G, Li Q. A coalitional game theoretic energy transaction algorithm for networked microgrids. Int J Electr Power Energy Syst 2023;144:108494.
[25] An D, Yang Q, Yu W, Yang X, Fu X, Zhao W. SODA: Strategy-proof online double auction scheme for multimicrogrids bidding. IEEE Trans Syst Man Cybern: Syst 2017;48(7):1177–90.
[26] Bandara KY, Thakur S, Breslin J. Flocking-based decentralised double auction for P2P energy trading within neighbourhoods. Int J Electr Power Energy Syst 2021;129:106766.
[27] Teixeira D, Gomes L, Vale Z. Single-unit and multi-unit auction framework for peer-to-peer transactions. Int J Electr Power Energy Syst 2021;133:107235.
[28] Xu S, Zhao Y, Li Y, Zhou Y. An iterative uniform-price auction mechanism for peer-to-peer energy trading in a community microgrid. Appl Energy 2021;298:117088.
[29] Haggi H, Sun W. Multi-round double auction-enabled peer-to-peer energy exchange in active distribution networks. IEEE Trans Smart Grid 2021;12(5):4403–14.
[30] Chen K, Lin J, Song Y. Trading strategy optimization for a prosumer in continuous double auction-based peer-to-peer market: A prediction-integration model. Appl Energy 2019;242:1121–33.
[31] Guerrero J, Chapman AC, Verbič G. Decentralized P2P energy trading under network constraints in a low-voltage network. IEEE Trans Smart Grid 2018;10(5):5163–73.
[32] Vakili R, Afsharnia S, Golshannavaz S. Interconnected microgrids: Optimal energy scheduling based on a game-theoretic approach. Int Trans Electr Energy Syst 2018;28(10):e2603.
[33] Fan S, Xu G, Ai Q, Gao Y. Community market based energy trading among interconnected microgrids with adjustable power. IEEE Trans Ind Appl 2022.
[34] Ghadimi M, Moghaddas-Tafreshi S-M. A decentralized operating model for a multi-microgrid system including private microgrids by using an auction-based day-ahead market framework. Int J Electr Power Energy Syst 2023;144:108547.
[35] Liu J, Samson SY, Hu H, Trinh H. A combinatorial auction energy trading approach for VPPs consisting of interconnected microgrids in demand-side ancillary services market. Electr Power Syst Res 2023;224:109694.
[36] An D, Yang Q, Li D, Wu Z. Distributed online incentive scheme for energy trading in multi-microgrid systems. IEEE Trans Autom Sci Eng 2023.
[37] Symiakakis MS, Kanellos FD. Towards the detailed modeling of deregulated electricity markets comprising Smart prosumers and peer to peer energy trading. Electr Power Syst Res 2023;217:109158.
[38] Nikolaidis AI, Charalambous CA, Mancarella P. A graph-based loss allocation framework for transactive energy markets in unbalanced radial distribution networks. IEEE Trans Power Syst 2018;34(5):4109–18.
[39] Huang P, Scheller-Wolf A, Sycara K. Design of a multi–unit double auction e–market. Comput Intell 2002;18(4):596–617.
[40] Vickrey W. Counterspeculation, auctions, and competitive sealed tenders. J Financ 1961;16(1):8–37.